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Tracing provenance and sediment fluxes in the Irrawaddy River basin (Myanmar)

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ABSTRACT

This study illustrates the petrographic, heavy-mineral, geochemical and geochronological signatures of sand transported by various branches of the Irrawaddy (Ayeyarwadi) River, one of the first in the world for sediment flux. Intrasample and intersample compositional variability, weathering and hydraulic-sorting controls are also discussed. Feldspatho-quartzose sand in Irrawaddy headwaters is largely derived first-cycle from mid-crustal metamorphic and plutonic rocks of the Mogok Belt and Lohit complex, whereas feldspatho-litho-quartzose Chindwin sand is largely recycled from supracrustal, sedimentary and very low-grade metasedimentary units. Additional mafic to ultramafic detritus is derived from ophiolites and blueschists exposed from the Indo-Burman Ranges to the Jade Mines and Myitkyina belts, linked northward to the Yarlung-Tsangpo suture of the Himalaya. Volcanic detritus derived from the Popa-Wuntho arc or recycled from forearc-basin strata also occurs. Decreasing concentration of most chemical elements along the Irrawaddy reflects progressive addition of detritus recycled from sedimentary rocks, most evident downstream of the Chindwin confluence. REE patterns with LREE enrichment and negative Eu anomaly reflect the occurrence of allanite, largely derived from granitoid rocks in the Mali catchment. Chemical indices indicate moderate weathering in the monsoon-dominated climate of Myanmar. Young U-Pb ages (15–170 Ma) represent 85% of detrital zircons in Irrawaddy headwater branches, reflecting long-lasting subduction-related magmatism along a ring of fire connecting with the southern and central Lhasa batholiths in Tibet and polyphase metamorphism in the Mogok belt. Chindwin sand contains larger amounts of finer-grained, recycled pre-Mesozoic zircons, also yielding early Mesoproterozoic to Archean ages.
Such different petrographic, heavy-mineral, geochemical and geochronological fingerprints characterizing sand in different river branches allowed us to calculate bulk-sediment and zircon-provenance budgets that converge to indicate equivalent sand supply from the Nmai and Mali Rivers to the upper Irrawaddy, and from the Chindwin and upper Irrawaddy to the lower Irrawaddy. This implies that despite of higher erosion potential indicated by stream-profile analysis in high-relief Irrawaddy headwaters, sediment yields and erosion rates are detectably higher in the Chindwin catchment, which is mainly ascribed to higher erodibility of widely exposed siliciclastic rocks. Quantifying sediment provenance and defining erosion patterns based on an integrated compositional database in a big-river system such as the mighty Irrawaddy allows us to expand our understanding of sediment-generation processes with the ultimate goal to increase our capacity to read into the stratigraphic record.

"When the timber-heavy streams of the monsoons debouch into the Irrawaddy, the impact is that of colliding trains. Fifty-foot tree trunks are sent shooting across the water like flat bottomed pebbles. The noise is that of an artillery barrage, with the sound of the detonations carrying for miles into the hinterland."

[Amitav Gosh, The Glass Palace]

1. Introduction

Geological, geomorphological and sediment-generation processes in big-river catchments can be investigated by several different methods (e.g., Gaillardet et al., 1999; von Blanckenburg, 2005; Borges et al., 2008; Hinderer, 2012; Clift, 2015). The compositional and geochronological signatures of detritus derived from an orogenic domain, which depend primarily on the lithology and time structure of source rocks and their evolution during progressive unroofing, provide an effective means to trace erosion processes in space and time (Garzanti, 2016). Any detrital component and any type of fingerprint (e.g., petrographic, mineralogical, geochemical, isotopic, geochronological) can be used as a provenance tracer to partition the sediment flux into its different sources (Padoan et al., 2011; von Eynatten and Dunkl, 2012), and

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hence to calculate average denudation rates in different parts of a river catchment once the total sediment load is known with reasonable accuracy (Bouchez et al., 2011; Syvitski and Kettner, 2011). Quantitative geomorphological techniques, such as the analysis of stream profiles and their deviation from equilibrium, represent an excellent independent tool to constrain such estimates, allowing us to identify those areas where river tracts are in disequilibrium, and thus most likely to have undergone recent uplift and rapid exhumation (Castelltort et al., 2012; Kirby and Whipple, 2012; Willett et al., 2014; Vezzoli et al., 2014, 2016).

The Irrawaddy (Ayeyarwadi) River, second in Indochina to the Mekong but third in the world for sediment flux according to Robinson et al. (2007), drains most of northern and central Myanmar, a region segregated for long by a military dictatorship that only in recent years has tolerated democratic elections and gradual transition to more open society. Limited information has been consequently made available on this huge river system, including a few data on detrital mineralogy, geochemistry and geochronology (Bodet and Schärer, 2000; Garzanti et al., 2013a; Limonta et al., 2016). And yet knowing the composition and compositional variability of Irrawaddy sediments is crucial to solve provenance problems such as the origin of turbiditic clastic wedges exposed along the eastern side of the Himalayan collision zone (Allen et al., 2007) and the evolution of big-river systems in south-eastern Asia (Robinson et al., 2014; Licht et al., 2016).

In this article we combine high-resolution petrographic, heavy-mineral, bulk-sediment geochemistry and U-Pb detrital-zircon geochronology analyses on modern sands collected in the entire Irrawaddy basin to assess the detrital fingerprints specific of principal tributaries and different trunk-river tracts (Fig. 1). Constrained further by the morphometric study of river profiles, this integrated database allows us to quantify sediment provenance and outline erosion patterns across the wide Irrawaddy catchment.

2. The Irrawaddy River

2.1. Hydrology and sediment flux

The Irrawaddy (Mali-Nmai-Hka for Kachin natives) originates at 150 m a.s.l. in Kachin State from the confluence of the wilder Nmai Hka ("bad river") and the quieter Mali Hka ("big river") more navigable despite its lower discharge (Stamp, 1940). Both headwater branches are sourced from high mountain glaciers at ~28°N in northernmost Myanmar, ~280 km SE of the eastern Himalaya syntaxis (Fig. 1A). The Irrawaddy (drainage basin ~430,000 km^2) flows southward across Myanmar for ~2170 km and empties through a delta with nine arms into the Andaman Sea. Average and maximum water discharge are estimated to be 13,000 m^3/s and 32,600 m^3/s, and annual suspended load to be as high as $364 \pm 60 \cdot 10^6$ tons (Robinson et al., 2007). An annual water discharge of 379 ± 47 km^3 and a suspended-load flux of $325 \pm 57 \cdot 10^6$ tons, with a significant decrease compared to the previous century, was calculated by Furuichi et al. (2009), based on data collected between 1969 and 1996 at Pyay well upstream of the delta. Its major Chindwin tributary (length ~1050 km, drainage basin ~115,000 km^2) has an annual discharge of ~165 km^3, reaching 300 km^3 in severe flood years (Zin et al., 2009; Chapman et al., 2015).

Most of the Irrawaddy basin is characterized by tropical monsoonal climate. Average temperatures in central Myanmar range between 25 °C and 30 °C during the wet season from May to October, when strong winds blow from the southwest bringing thunderstorms and heavy rain almost every day. They fall to 20–24 °C in the cold-dry season from November to February, and rise to 30–35 °C during the hot-dry season in March and April. Coastal regions may receive >5 m of rain annually, decreasing to ~2.5 m in the delta (2.7 m at Yangon) and to 0.5–1 m in the central plain (0.84 m at Mandalay). Annual precipitations increase up to ~4 m on the northern peaks, where climate is much cooler and snow falls in late autumn to early winter.

The Irrawaddy upstream of the Chindwin confluence (named "upper Irrawaddy" throughout this article) is joined progressively by the Taping, Shweli and Myitnge left-bank tributaries and by the Mu right-bank tributary. The Chindwin River, also sourced in northern Myanmar, runs southward along the eastern edge of the Indo-Burman Ranges, receives its right-bank Myitha tributary (*Myit* is "river" in Burmese), and finally joins the Irrawaddy in the middle of the central Myanmar forearc basin. Only minor tributaries contribute to the lower Irrawaddy between the Chindwin confluence and the sea.

The Irrawaddy is still a natural system scarcely affected by human activities. Only the Ava bridge, built by the British in 1933 near Sagaing, existed on the river until 1998. In 2007, Myanmar's military dictatorship signed an agreement for the construction of seven hydroelectric dams in the Nmai and Mali Rivers, including the large Myitsone Dam at their confluence. Construction began in 2009 but was suspended in 2011 after the harsh opposition of local communities and environmental organisations, concerned by the huge flooding area, relocation of ~15,000 people, earthquake hazards and ecological impact on biodiverse ecosystems. Two major dams exist along the Shweli (Shweli-1, 2008) and Myitnge Rivers (Yeywa Dam, 2010), but none along the Chindwin River.

2.2. Geology of river catchments

The Nmai River drains the Mogok metamorphic belt, consisting of amphibolite-facies gneisses and schists with diopside-bearing marbles, migmatites and granitoid intrusions, passing south-eastwards to lower-grade garnet and chlorite schists, and finally to Neoproterozoic turbidites and Paleozoic sedimentary rocks of the Shan Plateau (Bertrand and Rangin, 2003). The tectonic evolution of the Mogok Belt is still unclear. The available radiometric ages indicate two metamorphic events at least, one before and one after the intrusion of Upper Jurassic/Lower Cretaceous granitoids (Barley et al., 2003; Mitchell et al., 2007, 2012). The Mali branch drains mainly into the quartz-diorites and associated intrusives of the Lohit Plutonic Complex (Gururajan and Choudhuri, 2003), representing the eastward continuation of the Gangdese batholith of south Tibet (Lin et al., 2013; Fig. 2).

The Taping and Shweli tributaries have their headwaters in the N/S-trending Gaoligong Belt, running adjacent to the Salween (Nujiang) river valley and welding the Tengchong and Baoshan Blocks (Zhao et al., 2016). Instead, the Myitnge River drains entirely within the northern Shan Plateau (Fig. 1B), south-east of the southward continuation of the Nujiang suture. The Shan Plateau exposes a thick stratigraphic succession including Upper Cambrian siliciclastic and volcanic rocks, Ordovician to Devonian carbonates, black shales and quartzose sandstones, unconformably overlain by mid-Permian to mid-Triassic plateau limestones and followed in turn by Upper Triassic to Jurassic turbidites, limestones, shales and coal-bearing strata. Exposed along the N/S-trending Shan scarp to the west are locally metamorphosed Carboniferous-Lower Permian diamictites and folded Upper Jurassic to Lower Cretaceous clastic rocks and limestones. The Mu River flows along the central Myanmar forearc basin and is sourced in the largely Upper Cretaceous Wuntho Arc, correlative with the Lohit Plutonic Complex and the Gangdese batholith (Mitchell et al., 2012).

The Chindwin River incises into the Cretaceous to Cenozoic forearc-basin fill of central Myanmar (Oo et al., 2015), but also drains basement gneisses and the Jade Mines Belt in headwater reaches (Shi et al., 2014) and receives much of its sediments from Paleogene remnant-ocean turbidites of the Indo-Burman Ranges before cutting across largely Plio-Pleistocene arc-related volcanic rocks near Monywa (Stephenson and Marshall, 1984). Its Myitha tributary drains entirely within the retro-side of the Indo-Burman Ranges, where Upper Triassic flysch and ophiolites are exposed between Paleogene deep-water turbidites in the west and the Kabaw Fault in the east. The latter may represent the southeastern prolongation of the Indus-Yarlung ophiolitic suture zone of the Himalaya (Fig. 2).